Remotely sensed snowpack reconstruction improves Sierra Nevada water storage estimates

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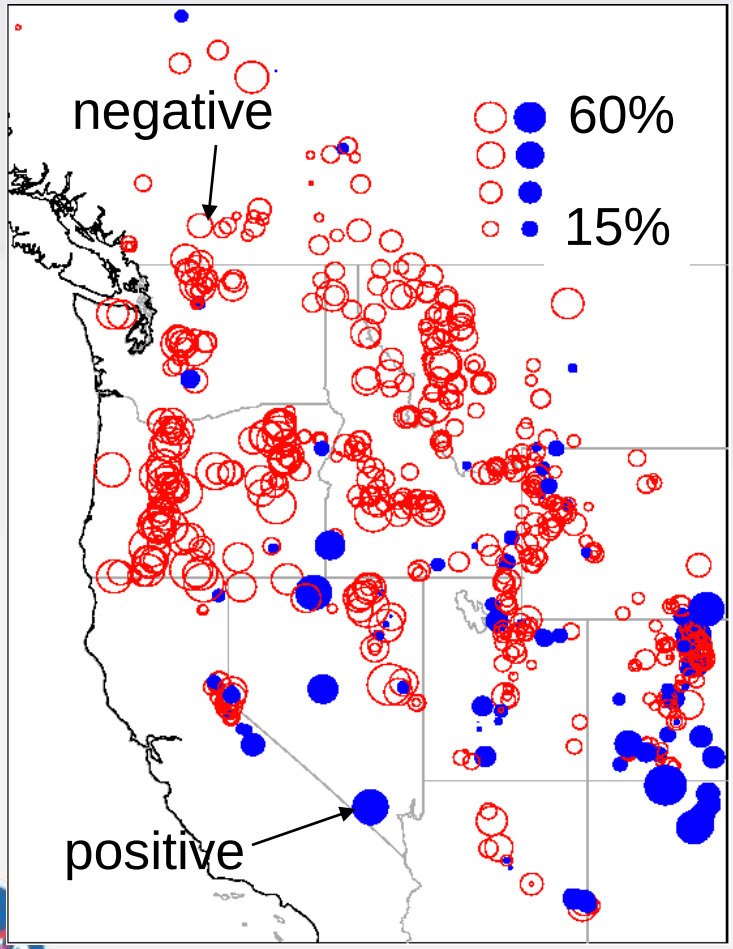
Snow water equivalent trend: 1950 -2000



Product: **Merged MODIS snow data with models to map SWE across Sierra Nevada.**

Motivation: Increases in regional temperature have decreased snow accumulation and shifted snowmelt earlier.

- death of stationarity

- need deterministic approach to runoff forecasting

- distributed snowpack information.

NASA/JPL Missions and Data: Water

NASA ASP Theme	*Outcomes*	*Spacecraft*	*Aircraft*	*Ground*	*Future*
Water Resource Management	Flow and flood forecasting	TOPEX/Poseiden, Jason-1, GRACE, AIRS, QuikSCAT, MODIS, CloudSAT, CALIPSO, AMSR-E	HAMSR, POLSCAT PALS	Surface radars, Weather Station	Aquarius(2009), SWOT (2013), GPM (2013)
	Water Supply, Drought Forecasting and Management	AMSR-E, QuikSCAT, MODIS	PALS	SNOTEL, SCAN, Surface radar, Weather station	SMAP (2012) CoReH2O SCLP
	Water Delivery and Irrigation	Terra, Aqua, GRACE, AMSR-E, QuikSCAT	PALS, GLISTIN	SNOTEL	SMAP (2012). DESDynI(2010), (SCLP (2016)
	Water Quality	CLoudSAT, CALIPSO, TRMM, MODIS, AMSR-E, GRACE, SRTM, ASTER		?	SMAP (2012), GPM (2013)

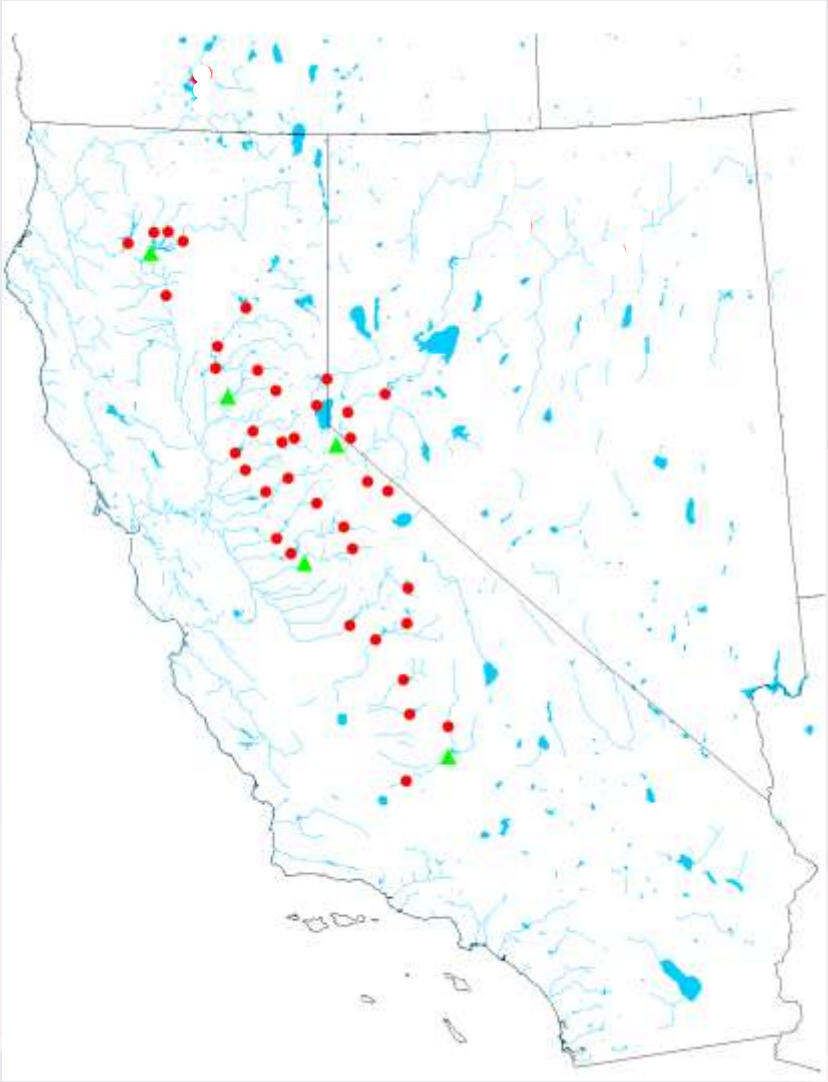
Building Bridges: Research-to-Operations

The question is: How do we integrate these measurements into operations?

Regression Formula variables include:

- October – March Precipitation Index
- April – July Precipitation Index
- High and Low Snow Indices
- Previous fall and spring runoff
- 50 year historic database (1956-2005)

- Water Supply Forecast Points



What is needed?

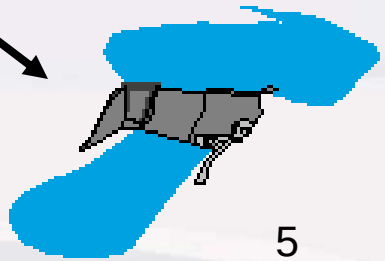
Identify the major issues faced by water resource managers that NASA resources may help address

- Climate change
- Short VS longer-term projections
- Death of stationarity

Empirical & regression methods

Precipitation forecast

Volume forecasts



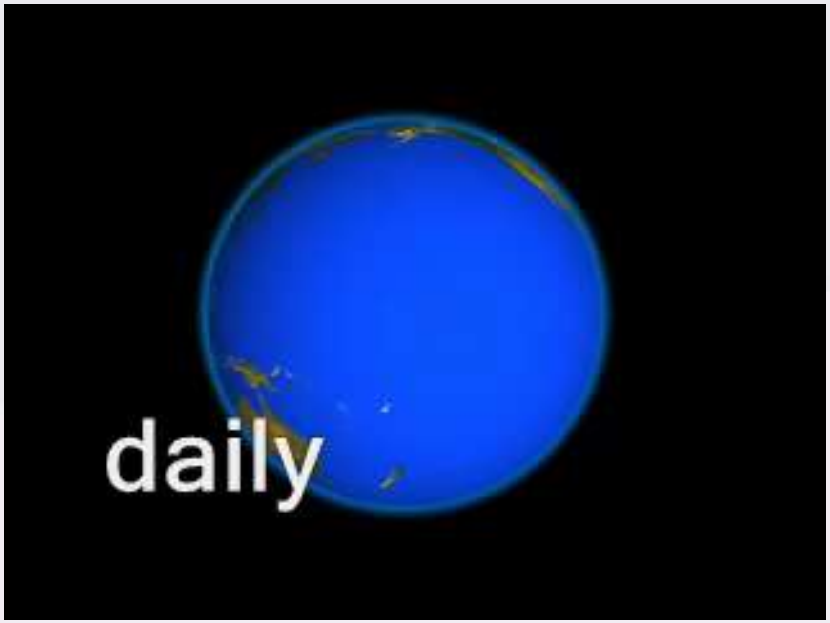
Decision making

What can NASA provide?

Identify the most important "information products" that NASA could provide to address these issues

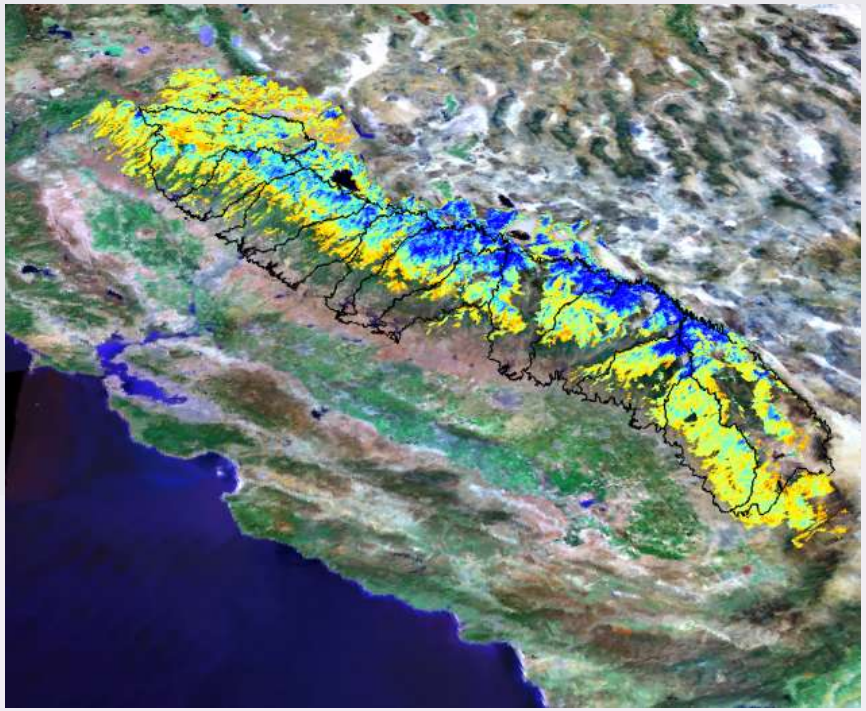
- Spatial distribution of SWE
- VIS / NIR synthesis products
-Airborne SWE detection

- Frequency? Resolution?



Product Development

- The low hanging fruit is the mountain snowpack.
  - Relatively easy detection of snow extent.
  - Relatively long satellite record.
- Can be used to evaluate inter-annual variability in snow cover persistence and snow water equivalent.



Product Development

Questions:

- How long? i.e. How variable is snow cover persistence?
- How much? i.e. How variable is snow water equivalent?

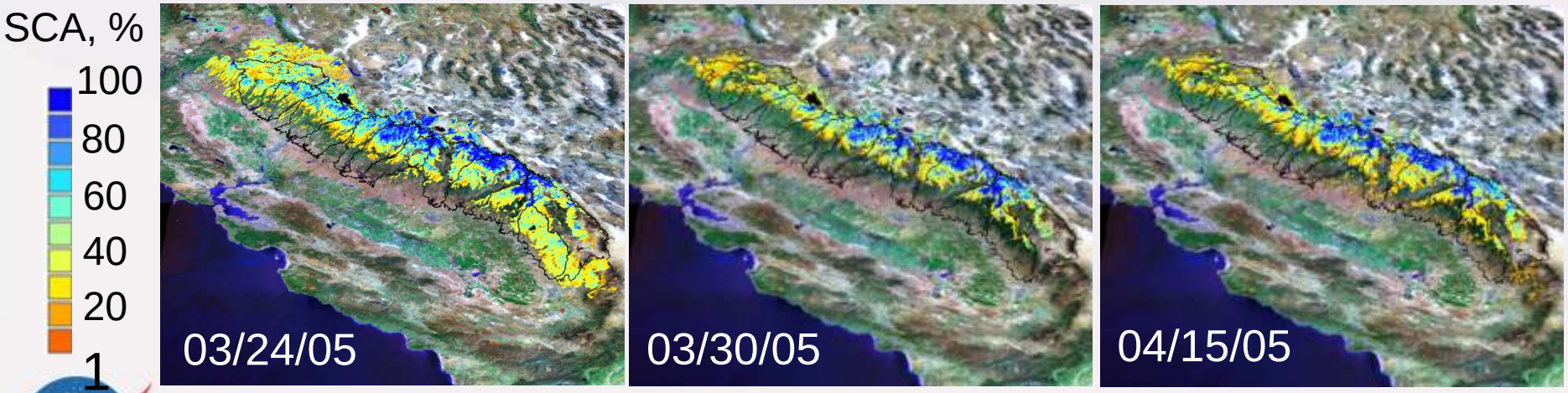
1) Develop time series of snow cover extent from satellite and evaluate patterns of snow disappearance.

2) Use snow disappearance data to reconstruct distribution of snow water equivalent.

Snow Cover Persistence From MODIS

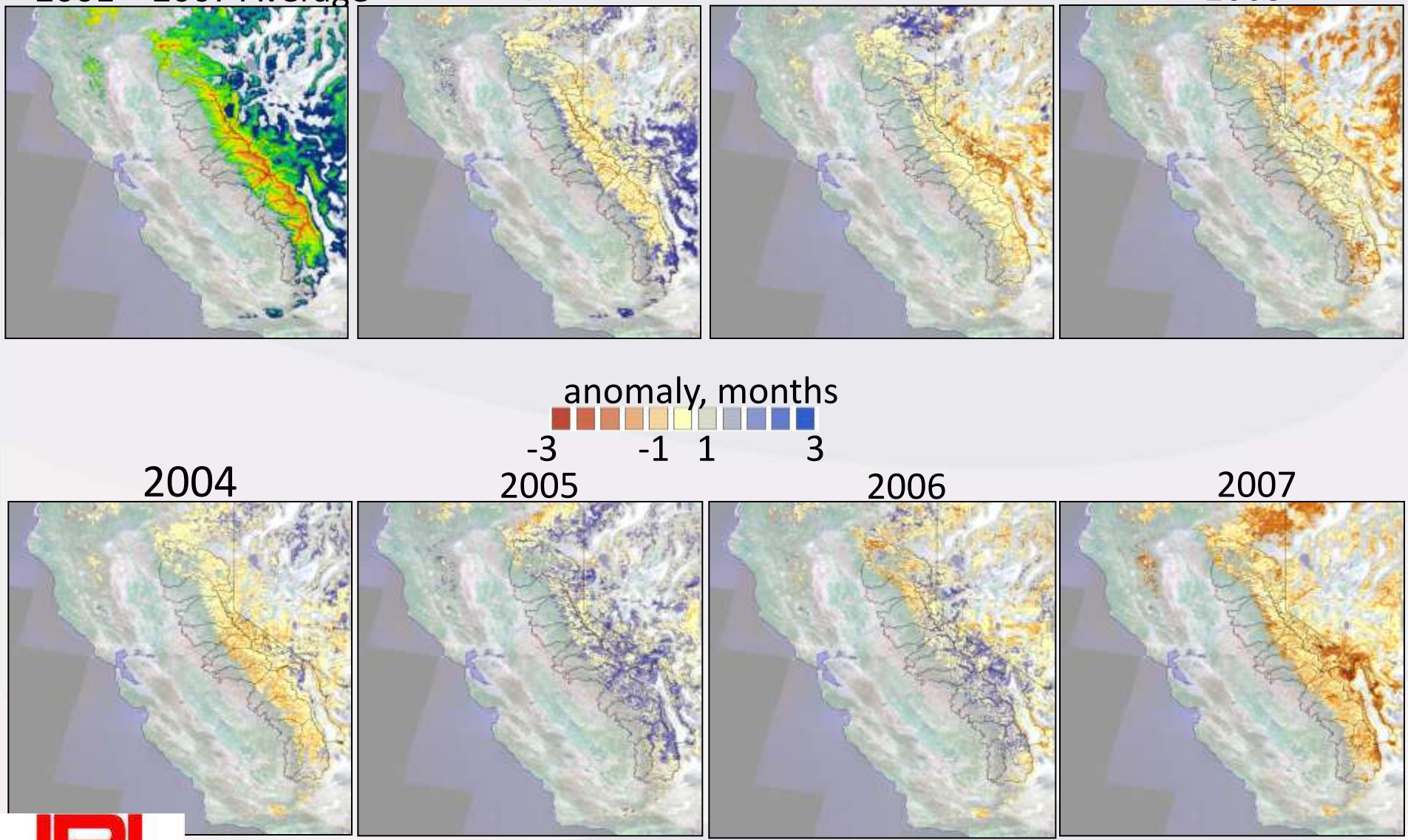
- For entire MODIS record (2001 – 2007) determine the persistence of snow (i.e. what month does snow disappear)

- For each year assign value 1 – 7 corresponding to a Jan - July snow disappearance.

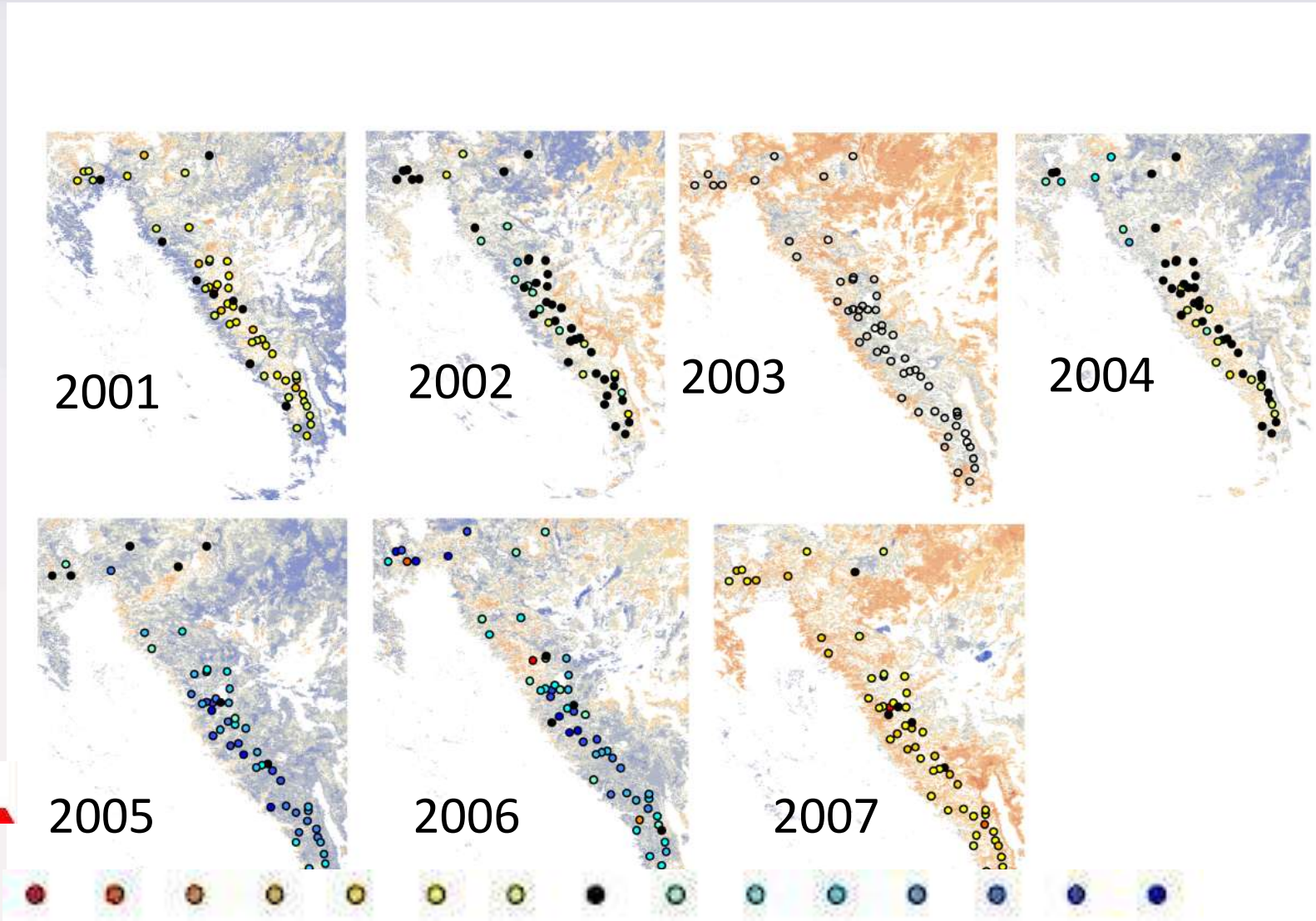


MODSCAG – Dozier et al., in press

Snow Cover Persistence Anomalies



Snow Cover Persistence & SWE Anomalies



Product Development: Integration of models and observations

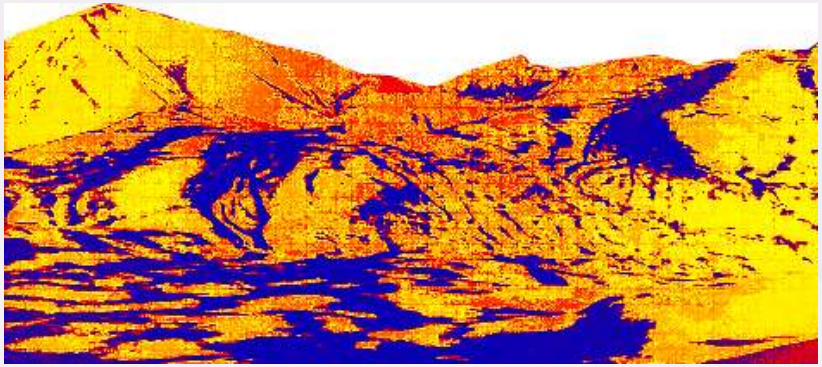
$$SWE_n = SWE_0 - \sum_{j=1}^{n} M_j$$

when $SWE_n = 0$,

$$SWE_0 = \sum_{j=1}^{n} M_j$$

snow covered area

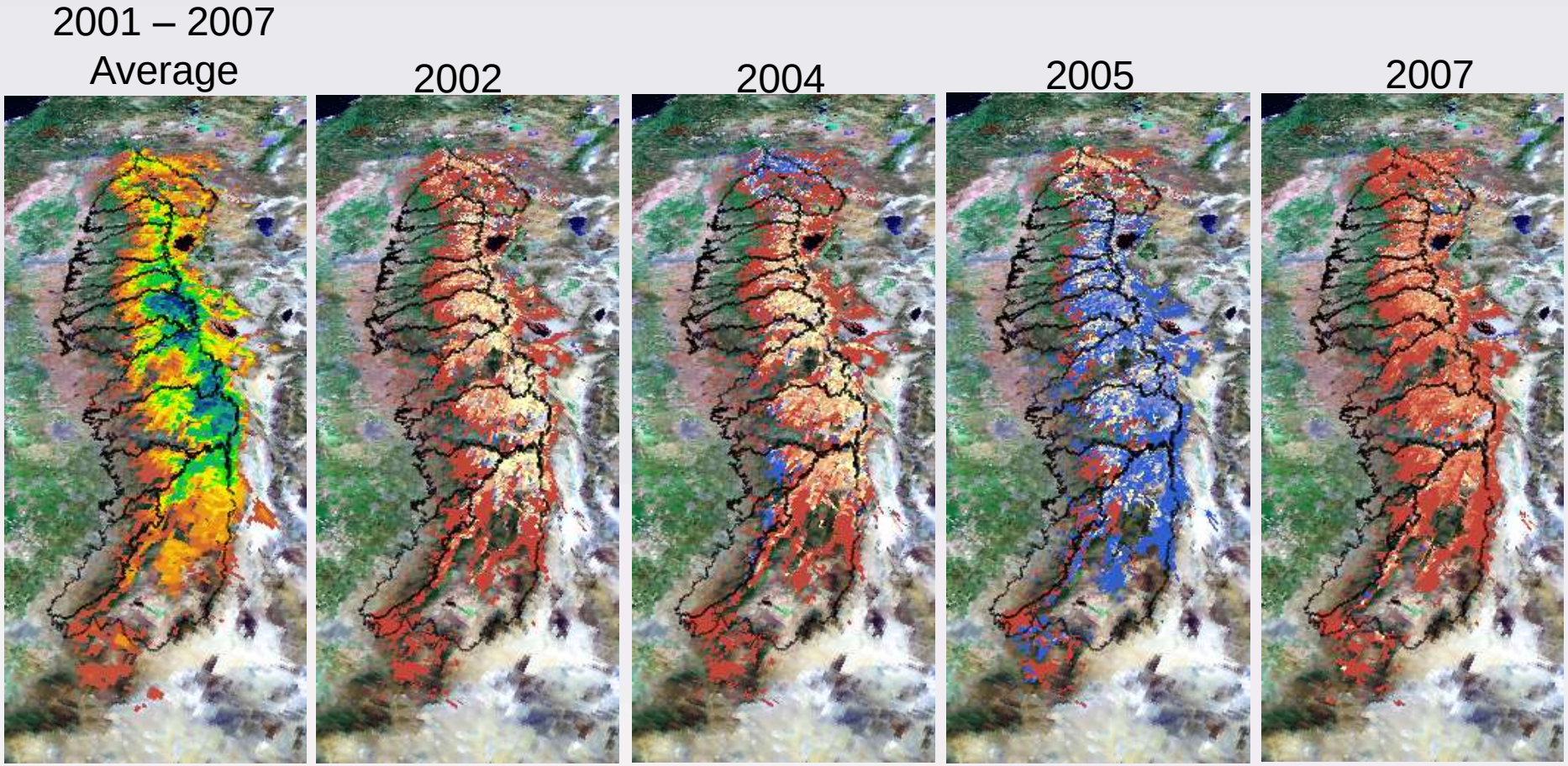
daily snowmelt, cm



0 1.6 3.2

Cline et al., 1998a,b; Liston, 1999; Molotch et al., 2004b; Molotch & Bales, 2005;2006; Durand et al., 2007; Molotch, 2008.

Snow Water Equivalent Anomalies



avg. SWE, cm

0 60 120 180

SWE anomaly, %

-100 -60 -10 10 60 100+

Molotch, 2009 – Hydrological Processes

science for a changing world

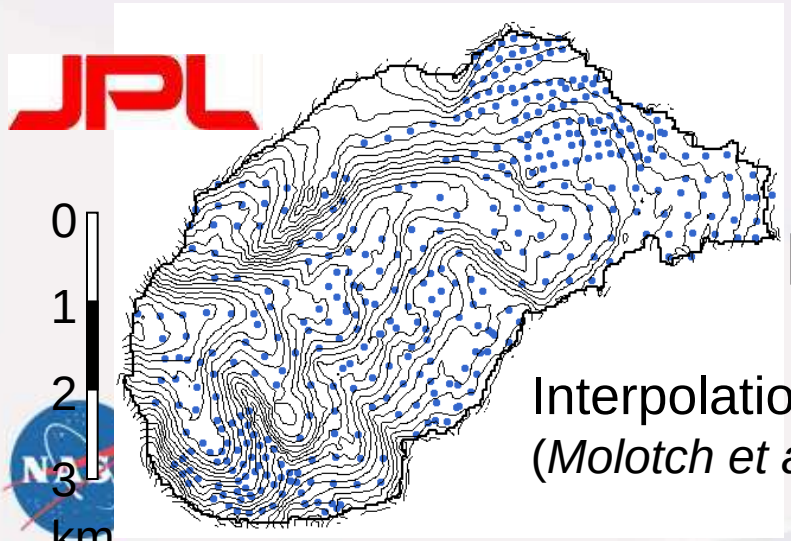
Ground-truth: Sierra Nevada, CA

snow depth

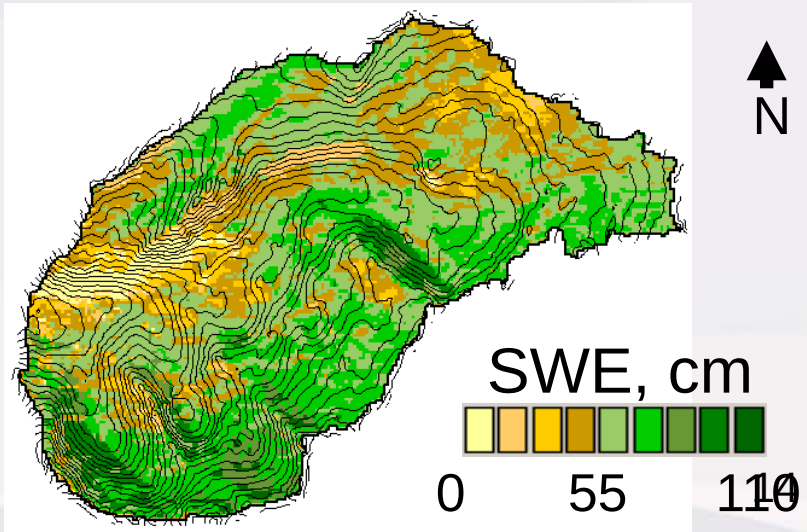
6 people
8 days

snow density

- 400+ measurements



Interpolation model
(*Molotch et al., 2004a*)

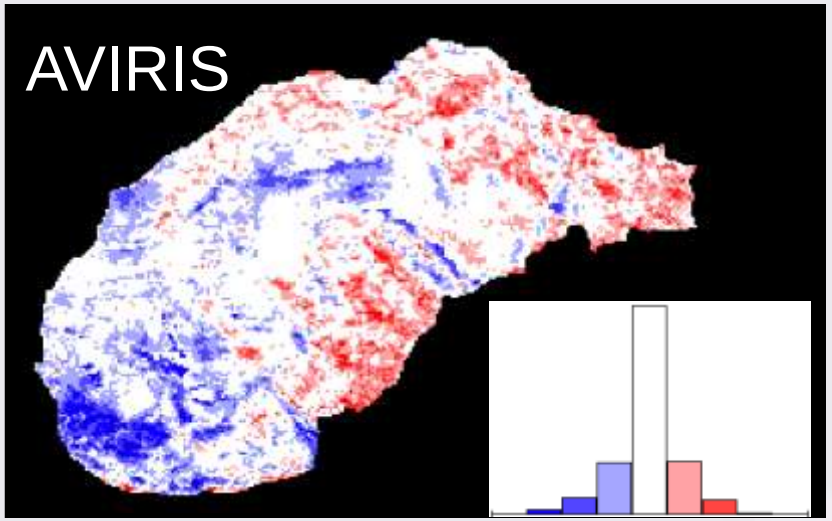


Ground-truth: Sierra Nevada, CA

- Mean absolute error of 2% across Tokopah Basin, Sequoia.

- Explain over 70% of runoff without calibration.

Modeled – Observed SWE

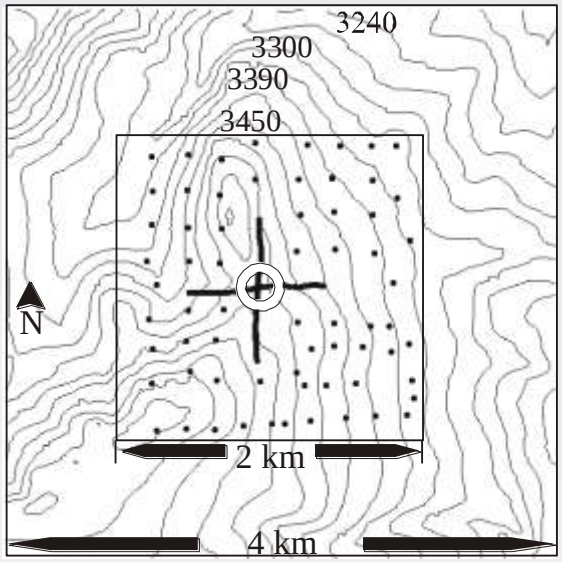


SWE difference, cm

-250 - -140
-140 - -105
-105 - -70
-70 - -35
-35 - 35
35 - 70
70 - 105
105 - 140
140 - 286

Molotch et al, 2004b – GRL;
Molotch & Bales, 2006 - WRR

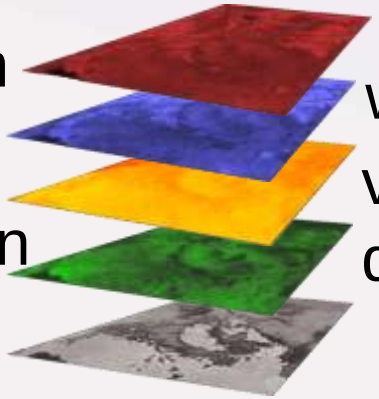
Ground truth: San Juan Mountains, CO



elevation

solar radiation

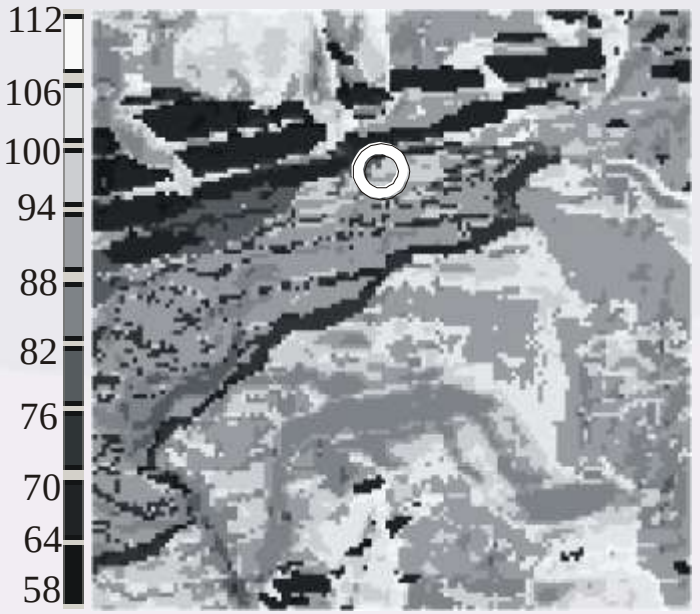
slope



wind exposure

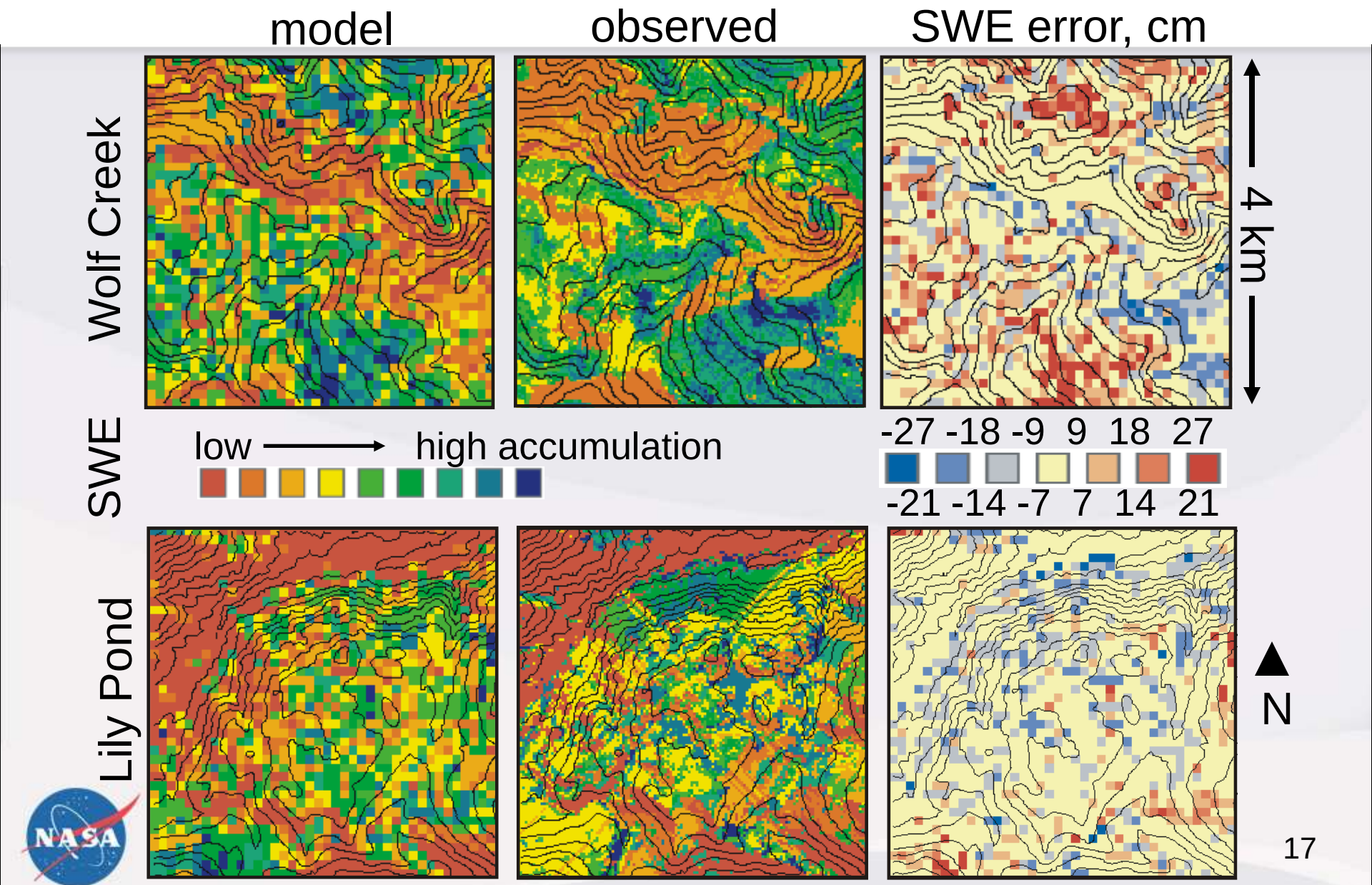
vegetation density

snow depth, cm



binary regression tree models (*Molotch et al., 2004*)

Ground truth: San Juan Mountains, CO

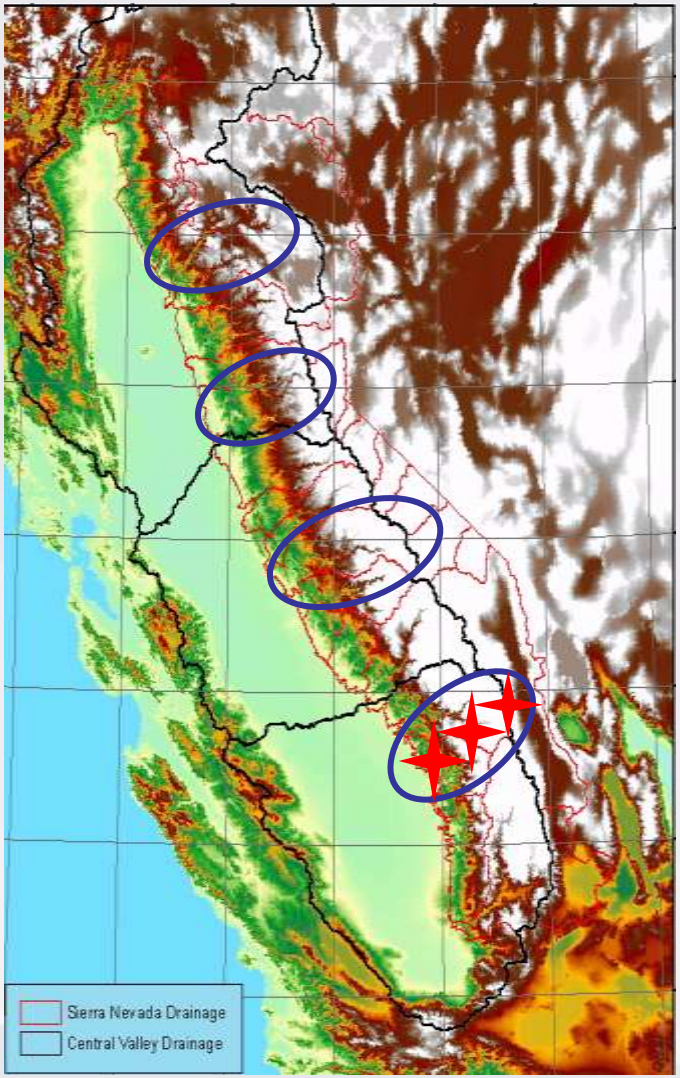


Sierra Nevada Hydrologic Observatory

Purpose:

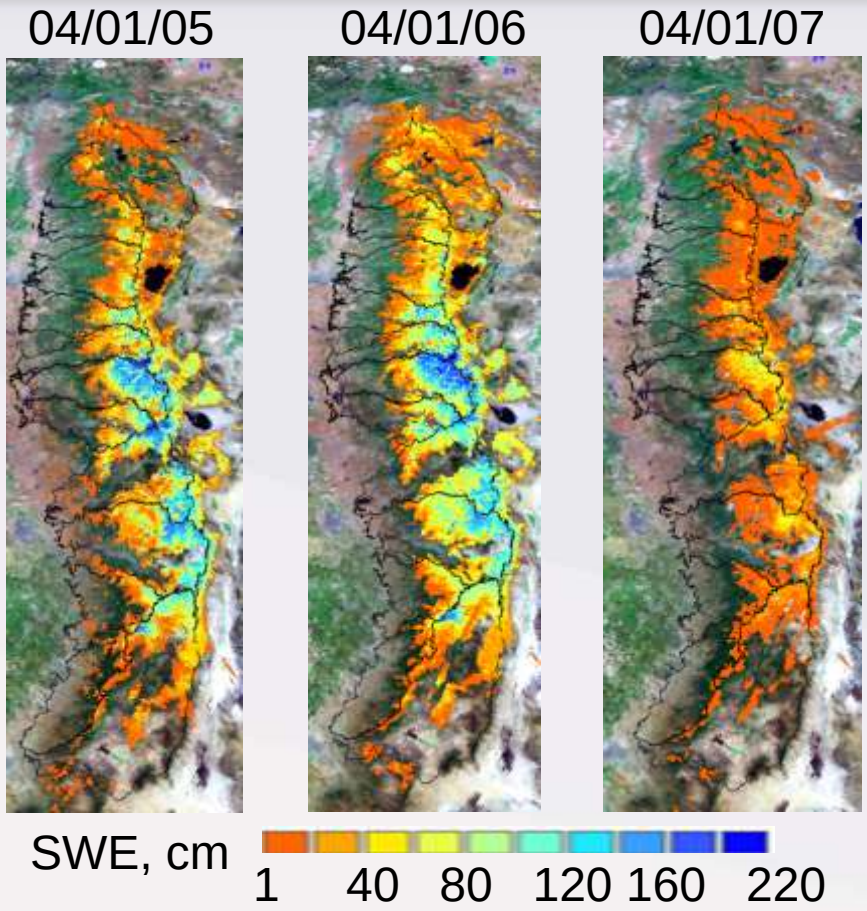
• observational infrastructure of the semi-arid west

• provide the foundation for the next generation of hydrologic modeling and management tools.



SNHO
Sierra Nevada Hydrologic Observatory

Moving Forward: Improve Seasonal Forecasts

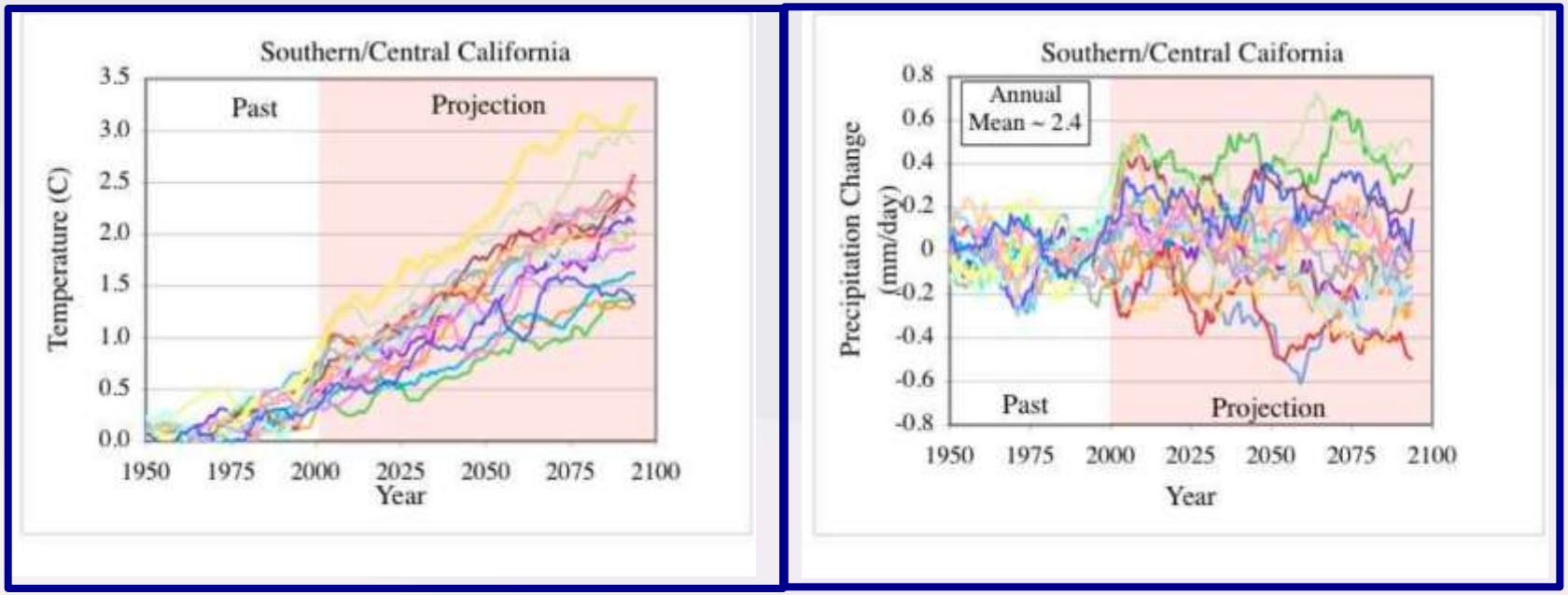


- **Merged MODIS snow data with models and sensor data to map SWE across Sierra Nevada.**
- **Evaluate retrospective case studies where regression models under-performed.**
- **Use products to determine processes controlling model performance.**
- **Identify ways to integrate product into regression based models.**

Molotch, 2009

Moving Forward: Improve Longer-Term Projections

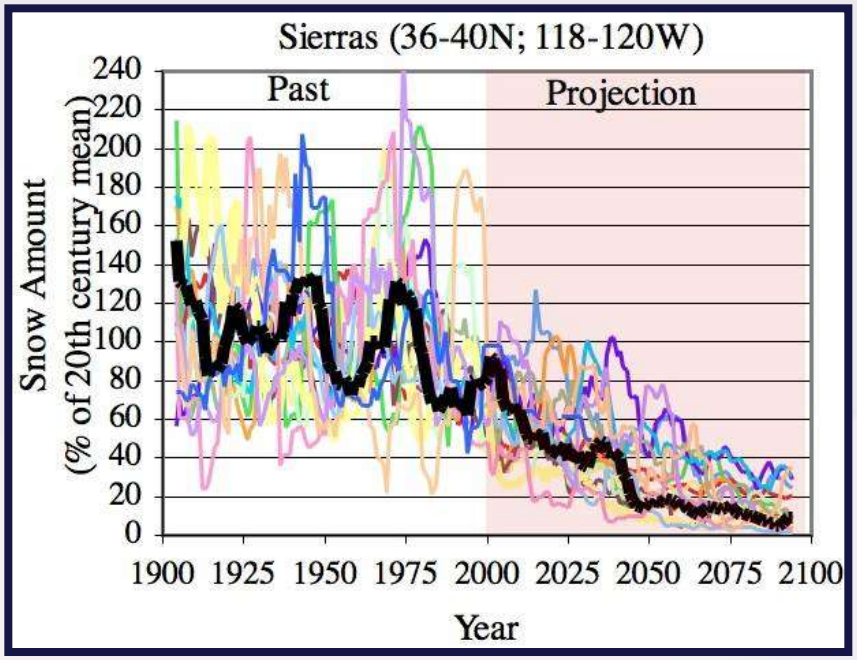
IPCC AR4 model projections agree that California will warm in this century but disagree on whether it will become wetter/drier. This implies that some physical processes are inadequately represented in GCMs.



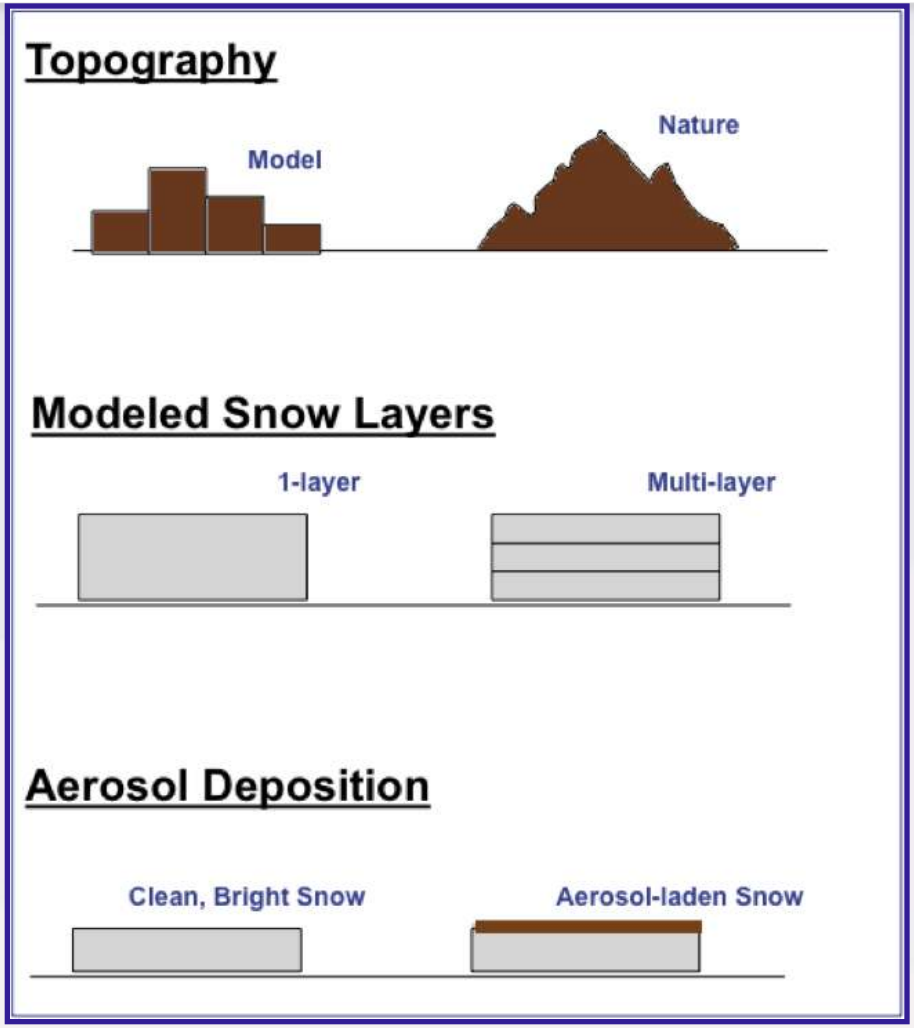
Apply our unique strengths in system engineering and observations (JPL) and process understanding and modeling (UCLA) to improve our capabilities to detect and predict changes in California's climate and ecosystems and contribute to the State's awareness and understanding, and adaptation and mitigation strategies.

Moving Forward: Improve Longer-Term Projections

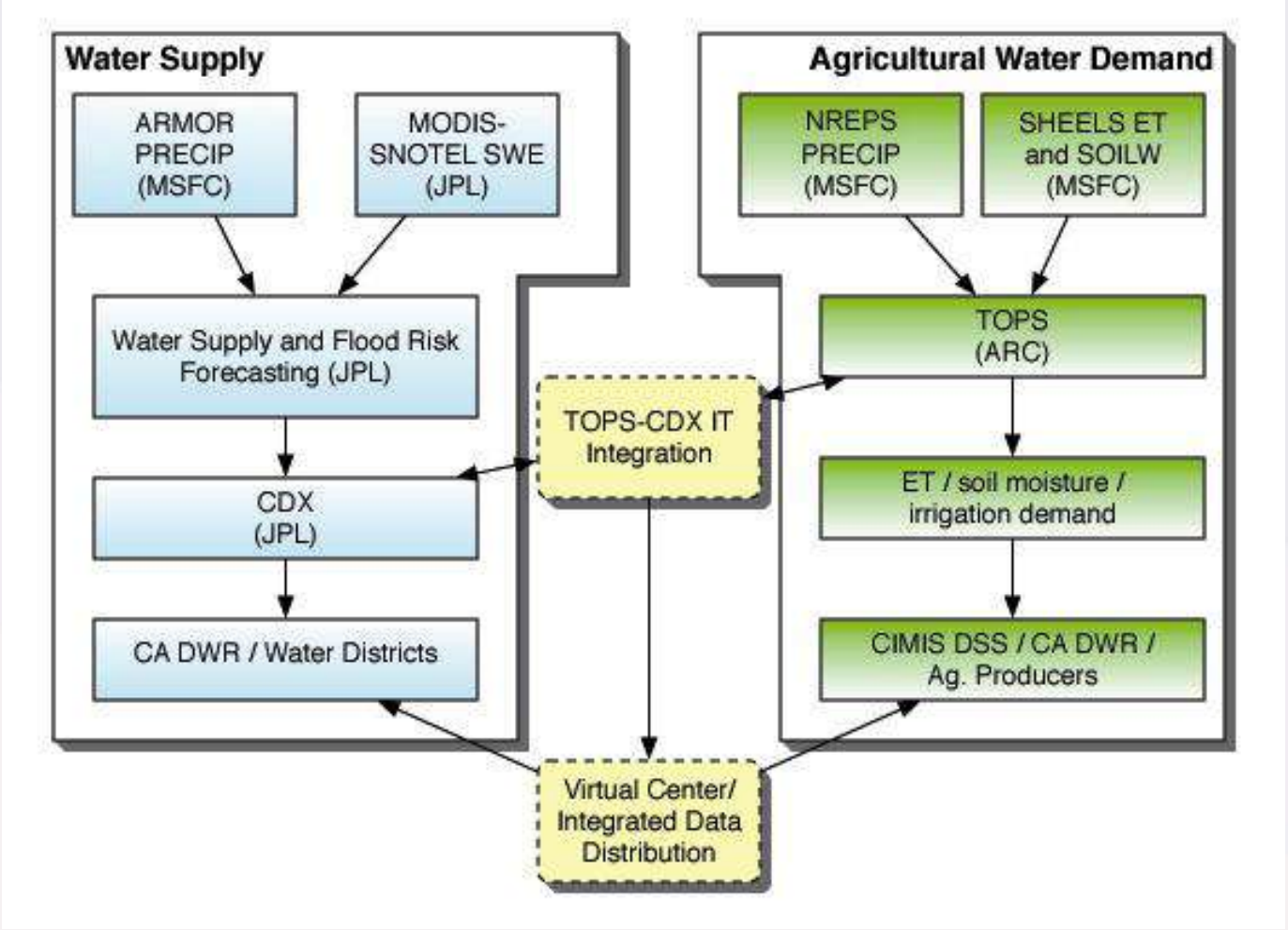
IPCC AR4 Projections



But how realistic?



Develop Integrated Framework



Acknowledgements

CA DWR

NASA Stimulus Team

NASA Applications Program

LADWP

NASA Terrestrial Hydrology Program

Remotely sensed snowpack reconstruction improves Sierra Nevada water storage estimates

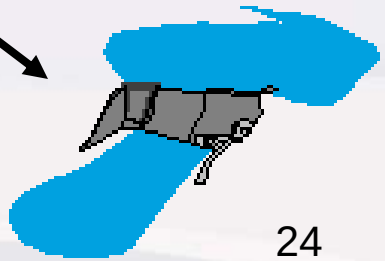
- **Users:** Water agencies and irrigation districts from local to federal levels (Eldorado Irrigation, East Bay Mud, Hetch Hetchy, LADP, NOAA-NWS, MWD, many others).

Empirical & regression methods

Precipitation forecast

Volume forecasts

Decision making



Remotely sensed snowpack reconstruction improves Sierra Nevada water storage estimates

Use Bayesian data assimilation approach to update snowpack estimates based on deviations between forward modeled snow cover and satellite observed snow cover.